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RESEARCH MEMORANDUM

THE EFFECT OF STICK-FORCE GRADIENT AND STICK GEARING ON THE TRACKING ACCURACY OF A FIGHTER AIRPLANE

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NATIONAL ADVISORY COMMITTEE
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THE EFFECT OF STICK-FORCE GRADIENT AND STICK GEARING ON THE TRACKING ACCURACY OF A FIGHTER AIRPLANE

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SUMMARY

Steady straight-and-level and steady turning tracking runs against an aerial target were made with an F-51H airplane, equipped with a fixed optical sight and having various combinations of maneuvering stick-force and stick-deflection gradients.

Over the complete range of control-system parameters covered (stick-force variation of 0.2 to 5.9 pounds per g and stick-deflection variation of 0.07 to 0.70 inch per g), excellent tracking could be accomplished, with standard deviations of pitch aim wander of less than 2 mils. Spectral densities of control-surface motion and stick-force variation indicated no significant or systematic variation of pilot's behavior or method of moving the controls with the variations in the control-system characteristics.

INTRODUCTION

This investigation is an extension of previous studies of the influence of various aerodynamic factors on the tracking accuracy of fighter airplanes (refs. 1 and 2). In these studies it was found that, in steady maneuvers with a fixed optical sight, excellent tracking was possible with a number of different airplane configurations and over a large variation of flight conditions. However, since all the configurations tested met United States Air Force handling-qualities specifications (ref. 3) over most of their operating range, only a relatively small variation in control-force gradient was covered, especially in the low force range. For this reason, the present investigation was undertaken in which the effect of variations in the elevator control-force gradient on the tracking performance was studied.

The scope of the investigation was limited for the most part to the region of low to moderate stick-force gradients. In addition, the effects

of various ratios of stick-to-elevator deflection were investigated. It was felt that the region of very low forces and very small stick deflections, where problems of high control sensitivity could exist, was of particular interest. Previous results (ref. 1 for the F-86A at high Mach numbers) indicated that satisfactory tracking could be achieved with stick-force gradients high enough to be objectionable to the pilot (and lying outside the satisfactory limits as set forth in reference 3), even though it required the use of the adjustable stabilizer as a primary control to correct for gross errors.

NOTATION

A_Z	normal acceleration factor, g units
f	frequency, cps
F_s	elevator stick force, lb
G	$G_y(f) = 4\int_0^\infty \overline{[y(t)-\bar{y}]\,[y(t+\tau)-\bar{y}]}\cos(2\pi f\tau)\,d\tau$, power spectral density, (units of y)^2/cps
g	acceleration of gravity, ft/sec^2
h_p	pressure altitude, ft
M	Mach number
S	G/σ^2, normalized power spectral density, per cps
t	time, sec
x_s	elevator stick deflection, measured at stick grip, in.
δ	elevator deflection, deg
Δ	$\Delta(\ )$ indicates changes in ( ) from trim value
ϵ	pitch aim error, mils
σ	$\sigma_y = \sqrt{\overline{[y(t)-\bar{y}]^2}}$, standard deviation, units of y
$\overline{(\ )}$	$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$, mean, units of y

TEST EQUIPMENT, PROCEDURES, AND METHOD OF ANALYSIS

Test Equipment

An F-51H airplane, equipped with a Navy Mark 8 Mod 5 fixed optical sight (identical to the one described in reference 1), was used as a test vehicle. The airplane was provided with a control-stick assembly that was modified by the addition of linkages connected by a lead screw drive so that the ratio of control-stick to elevator deflections could be varied in flight from approximately half to twice normal. In addition, various amounts of ballast were added to the tail compartment in order to vary the maneuvering elevator-angle gradient. By using various combinations of stick-to-elevator-deflection ratios and ballast the range of maneuvering stick-force and stick-deflection gradients shown on figure 1 was obtained. In providing the above modifications, a direct mechanical link between the stick and elevator was maintained so that whatever stick forces were present were primarily a result of the elevator hinge moments, as is the case for the normal F-51H airplane and other airplanes not equipped with fully powered controls.

Test Procedures

The standardized gunnery maneuver described in reference 1 was used for the present tests. In this maneuver the fighter tracks the target at a range of approximately one thousand feet in straight and level flight for a period of about thirty seconds, after which the target breaks as rapidly as possible into a steady turn of a given normal acceleration and the fighter again tracks the target for about thirty seconds after steady conditions have been reached. In this report no data concerning the transition region from steady straight to steady turning tracking have been presented. In general, as was found for the normal F-51 configuration in reference 1, the transition regions were of short duration with only slight increases in the aim wander over the complete range of control-system parameters covered. In addition, since the results of reference 1 indicated very little variation of aim wander with speed, altitude, and normal acceleration in the turn, the majority of the data for the present tests were taken at a Mach number of 0.5, an altitude of 20,000 feet, and a target turn of approximately three g. Also, since the results of both references 1 and 2 indicated very little variation of aim wander in smooth air with the airplane dynamic response characteristics, it was felt that the variation of longitudinal period and damping due to the variation in static margin in the present tests would not significantly affect the results. The period, computed from wind-tunnel derivatives, varied from 1.7 second for the normal F-51H to 2.7 seconds for the rear center-of-gravity location. The cycles to damp to half-amplitude were computed to vary from 0.20 for the normal F-51H to 0.09 for the rear center of gravity.

Method of Analysis

The methods of analysis discussed in reference 1 were also applied to the data gathered in the present tests. Means, standard deviations, and power spectral densities of aim wander, elevator movements, and stick-force variations during tracking in steady straight and steady turning flight were computed using IBM electronic equipment.

In computing the spectral densities, corrections for the effect of the mean on the low frequency points were applied. This was done because, with the method of computation used (ref. 4), the effect of the mean is carried over to the second frequency point and tends to obscure the low frequency content of the wander about the mean. This is especially true of the elevator-movement and stick-force spectra for the steady turns where relatively large means occur.

The results are plotted as normalized power spectral densities. This is done in order to emphasize the relative variation in frequency content between runs, since in some cases the levels of the spectral densities for identical conditions are quite different due to differences in the standard deviation. The normalized spectral density is:

$$S = \frac{G}{\sigma^2} \tag{1}$$

The area under S equals unity and the actual spectral density (with the effect of the mean suppressed) can be obtained by multiplying the ordinates by the square of the standard deviation.

RESULTS AND DISCUSSION

Means and standard deviations of aim wander, elevator movement, and stick-force variation for the various test conditions are listed in table I. On figure 2 are plotted standard deviations of pitch aim wander as a function of both stick-force gradient and stick-deflection gradient. It can be seen that there is no significant variation of aim wander with these quantities over the range covered in the present studies.

On figure 3 are plotted the standard deviations of elevator movement and on figure 4 are the standard deviations of stick-force variation. It can be seen that, like the aim wander, there is very little systematic variation of elevator movement with either stick-force or stick-deflection gradient. However, the standard deviations of stick-force variation, if separated according to center-of-gravity position, apparently increase systematically with stick-force gradient and decrease with stick-deflection gradient. This can be explained by considering

the control friction involved. For the normal F-51H control- to elevator-deflection gearing, 3 pounds of control friction are present, as felt at the stick grip. As the gearing is varied, the control friction varies in inverse proportion to the gearing. Since at both center-of-gravity positions the control-stick- to elevator-deflection gearing is 2.20 times the normal gearing for the points of maximum stick-deflection gradient and 0.46 times the normal gearing for the points of minimum stick-deflection gradient, the corresponding control frictions are 1.36 pounds and 6.52 pounds, respectively. Figure 5, in which the control-force standard deviations are replotted versus control friction, clearly shows the effect of the amount of control friction on the stick-force standard deviations. However, since a large portion of the stick-force variations lie within the friction band, the same trend does not carry through to the elevator motions (fig. 3) or to the aim wander (fig. 2).

It should be emphasized that the control system used in these tests was conventional in the sense that a direct link existed between the control stick and the elevator. The friction was due to control cables, fittings, etc. The test results would not necessarily apply to a system with powered controls, especially if the friction forces should arise in a hydraulic control valve. Reference 5 compares the effects on the general handling qualities of various types of friction and breakout force.

Apparently, a human pilot can readily adapt himself to variations in control characteristics so that he applies whatever stick forces and deflections are necessary to maintain small aim wander. It should be pointed out that the lower force gradients tested were definitely considered unsatisfactory by the pilot from a general handling qualities point of view (and are outside the satisfactory limits as set forth in reference 3). Nevertheless, even though the pilot felt it required more concentration and effort to track at these conditions, excellent accuracy was obtained. Of the various conditions tested, the pilot commented most favorably on a stick-force gradient of 1.2 pounds per g and a stick-deflection gradient of 0.70 inch per g. Note that this is the largest stick-deflection gradient tested and that a minimum of control friction is present. However, it should be pointed out that this condition should not be considered an optimum since points lying between the test extremes were not investigated.

In an effort to correlate the pilot's opinions with experimental data, spectral densities of elevator movement and stick-force variations, in addition to the aim-wander spectral densities, were computed. It was felt that perhaps significant variations in the frequency content of the control movements would occur which would be indicative of variations in the pilot's effort. Figures 6, 7, and 8 are normalized spectral densities of aim wander, elevator movement, and stick-force variation for two representative steady turning runs. Figures 9 through 12 are normalized spectral densities of elevator movement and stick-force variation for several extreme values of test conditions. In general, there is little significant

variation in the results. It is seen that variations between runs at the same conditions are as large as variations between conditions. In addition, no correlation between the shape of the curve (i.e., whether the amplitude falls off steadily with increasing frequency or whether it peaks at an intermediate frequency) and the resulting standard deviation of aim wander was found. Apparently, the variations in control-system parameters covered in the tests had no significant or consistent effect on the behavior of the pilot, even though they affected his opinions on the effort required to track. He could track with excellent accuracy whether it required more or less effort on his part.

CONCLUSIONS

The results of the investigation indicated that:

1. Over a range of stick-force and stick-displacement gradients of 0.2 to 5.9 pounds per g and 0.07 to 0.70 inch per g, respectively, excellent tracking, with standard deviations of pitch aim wander of less than 2 mils, could be accomplished.

2. Over the range of control-system parameters investigated, spectral densities of control-surface movement and stick-force variation indicated no systematic variation of the pilot's behavior or method of control.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Sept. 28, 1954

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5. Phillips, William H., Brown, B. Porter, and Matthews, James T., Jr.: Review and Investigation of Unsatisfactory Control Characteristics Involving Instability of Pilot-Airplane Combination and Methods for Predicting These Difficulties from Ground Tests. NACA RM L53F17a, 1953.

TABLE I.– MEANS AND STANDARD DEVIATIONS OF PITCH AIM WANDER, ELEVATOR MOVEMENT, AND STICK–FORCE VARIATION

$\frac{\Delta F_s}{\Delta A_z}$	$\frac{\Delta x_s}{\Delta A_z}$	Nominal A_z	$\bar{\epsilon}$	σ_ϵ	$\bar{\sigma}_\epsilon$	$\bar{\delta}$	σ_δ	$\bar{\sigma}_\delta$	$\bar{F}_s$	σ_{F_s}	$\bar{\sigma}_{F_s}$
0.2	0.34	1	−0.69	1.10	1.08	2.76	0.045	0.040	−0.97	0.62	0.64
		1	−.53	1.05		2.72	.035		−.98	.66	
		3	.19	1.88	1.57	1.89	.087	.086	1.38	1.06	1.01
		3	.73	1.26		1.93	.084		1.71	.95	
.5	.16	1	.02	.79	.77	2.73	.059	.050	.44	.98	.98
		1	−.19	.53		– –	– –		– –	– –	
		1	−.14	.37		– –	– –		– –	– –	
		1	−1.17	.92		– –	– –		– –	– –	
		1	−.23	.54		2.61	.041		– –	– –	
		1	.60	1.46		– –	– –		– –	– –	
		2	−.69	1.54	1.21	2.42	.058	.076	4.39	1.14	1.14
		2	.11	.90		– –	– –		– –	– –	
		2	.13	.41		– –	– –		– –	– –	
		4	−.04	1.91		– –	– –		– –	– –	
		4	.75	.98		1.54	.094		– –	– –	
		4	.60	1.46		– –	– –		– –	– –	
1.2	.70	1	.51	1.22	1.31	2.56	.034	.037	−.90	.45	.49
		1	−1.29	1.40		2.53	.040		−.88	.53	
		3	.67	1.26	1.23	1.33	.096	.082	4.30	1.15	1.30
		3	.59	1.19		1.20	.068		4.15	1.45	
1.1	.07	1	−.84	1.41	1.02	2.82	.052	.045	.13	1.29	1.47
		1	.19	.62		2.81	.037		.40	1.64	
		3	.60	1.11	1.44	1.93	.063	.062	9.57	2.06	2.06
		3	.41	1.76		1.96	.061		9.94	2.06	
2.7	.32	1	.49	2.09	1.41	2.59	.063	.049	−5.28	.77	.87
		1	.15	.72		2.64	.035		−3.30	.96	
		3	.48	1.06	1.03	1.37	.048	.049	5.77	1.10	1.23
		3	.71	1.00		1.36	.049		8.10	1.36	
5.7	.52	1	– – –	– –	[a].90	−.92	.019	.019	– –	– –	
		1	– – –	– –		−.70	.018		– –	– –	
		2	– – –	[a]1.37	1.46	−1.39	.029	.046	– –	– –	
		4	– – –	[a]1.54		−1.94	.063		– –	– –	
5.9	.15	1	−.22	.66	.70	2.60	.036	.036	−7.90	1.69	1.54
		1	−.18	.73		2.61	.036		−5.17	1.38	
		3	.78	1.29	1.16	1.20	.075	.057	17.99	2.12	1.80
		3	.68	1.02		1.23	.039		20.48	1.48	

[a]From reference 1.

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[redacted]

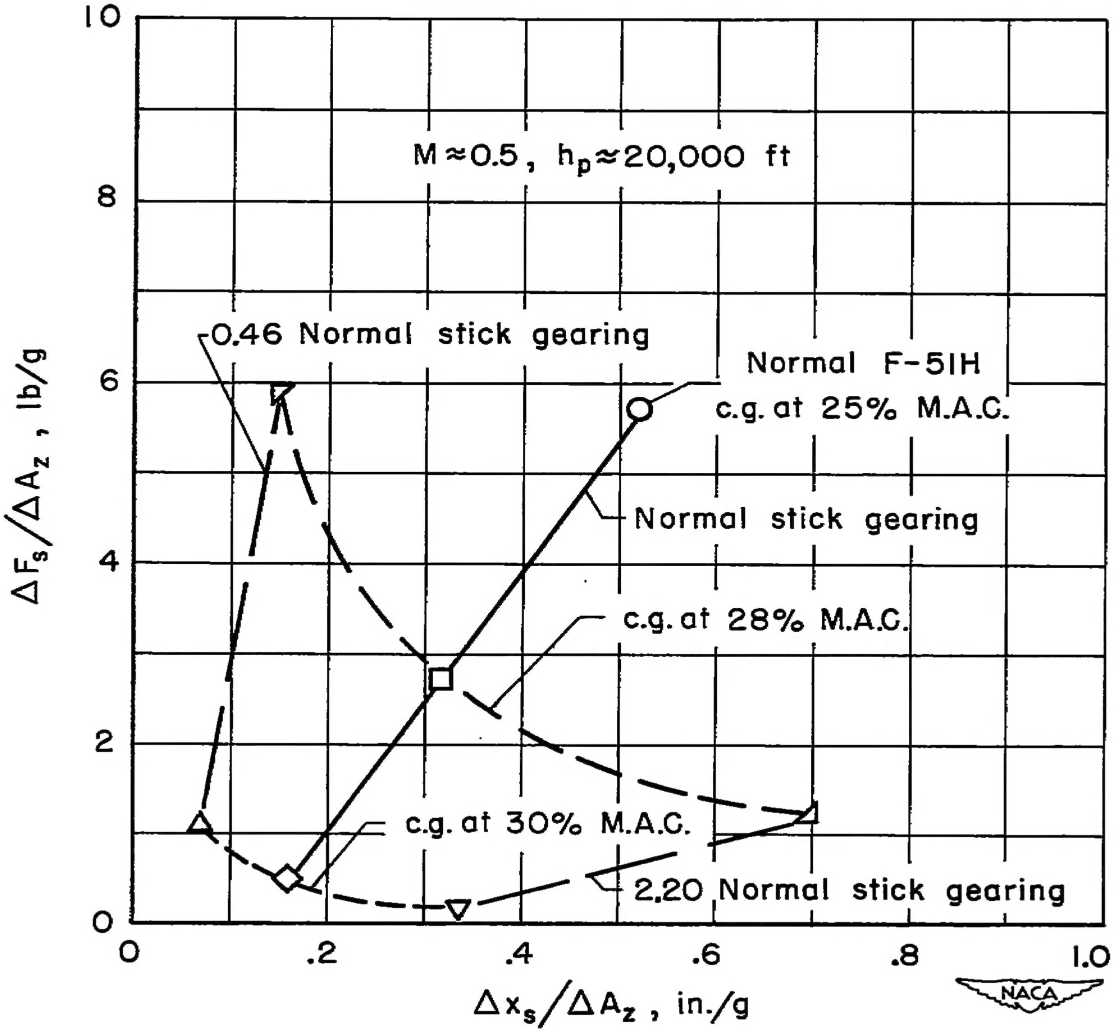

Figure 1.– Variation of longitudinal control parameters.

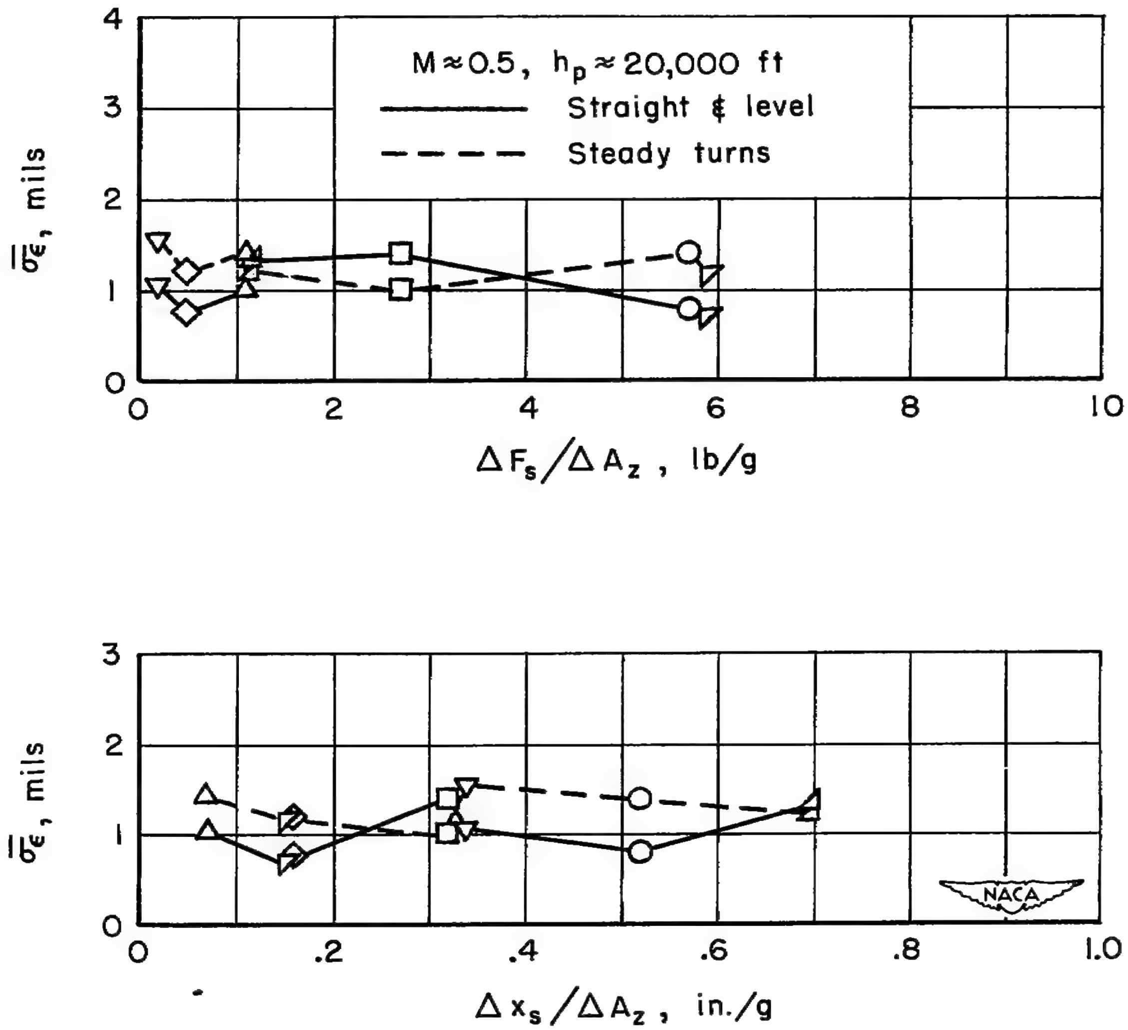

Figure 2.— Average standard deviations of aim wander.

[redacted]

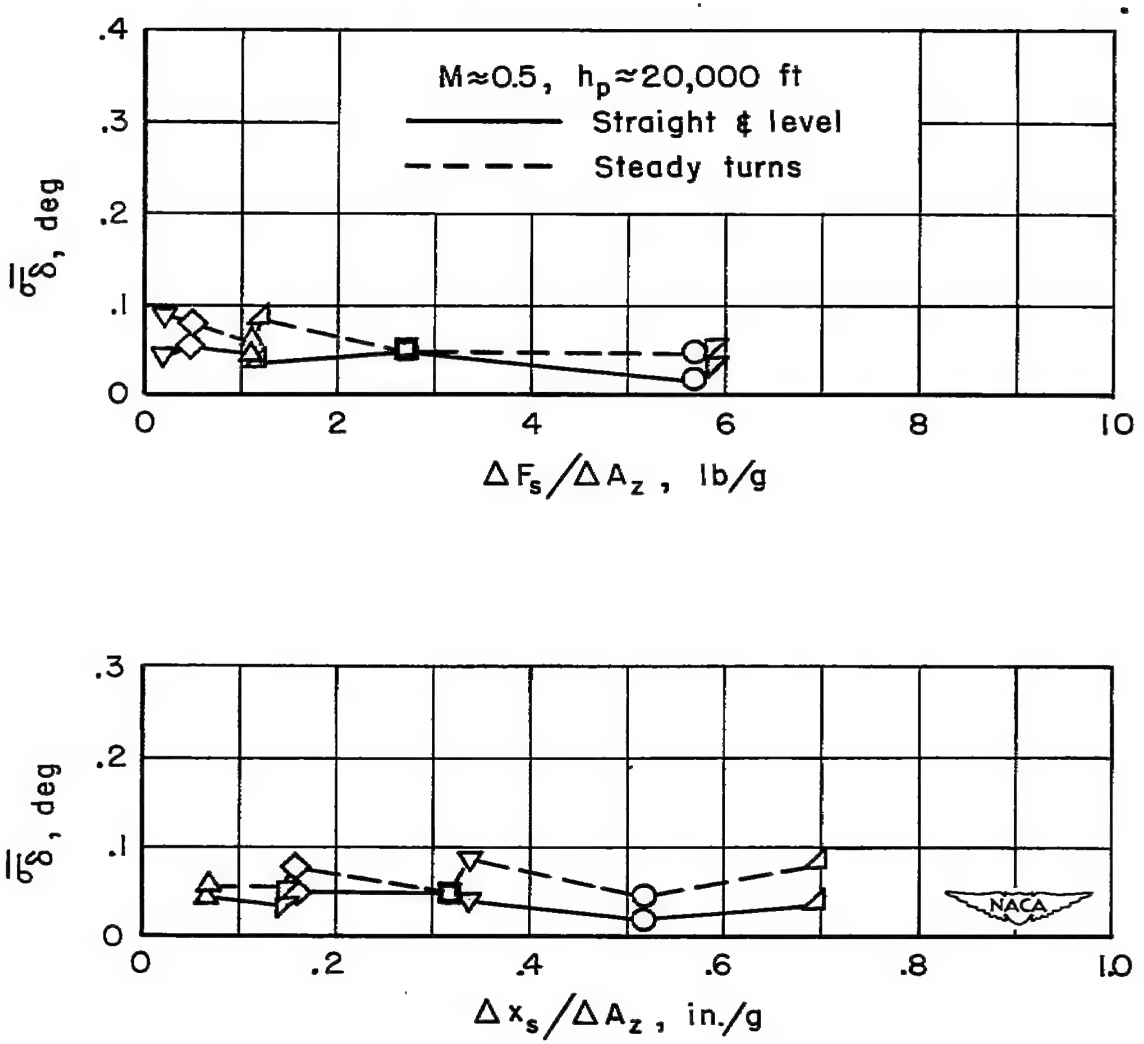

Figure 3.– Average standard deviations of elevator movement.

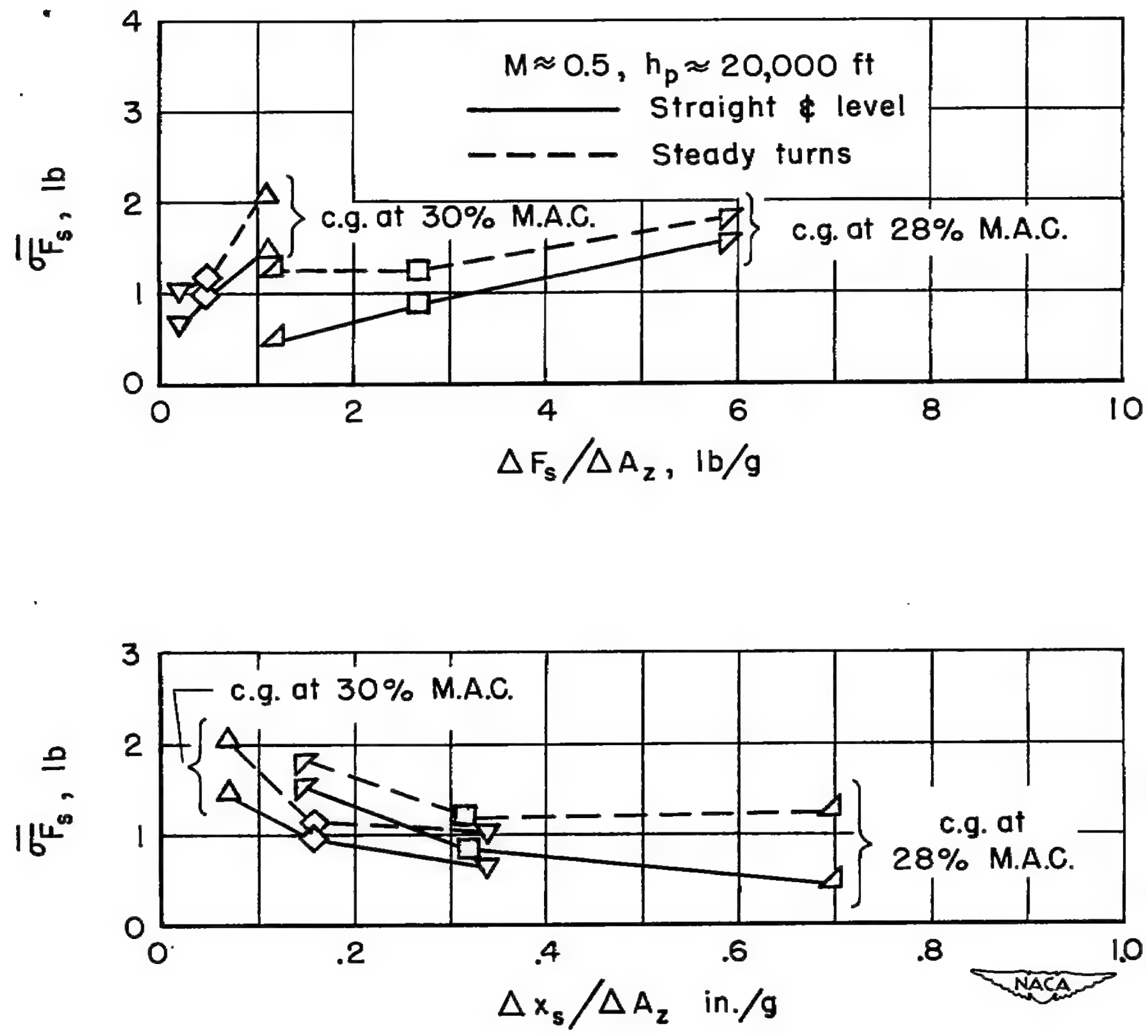

Figure 4.– Average standard deviations of control-force variations.

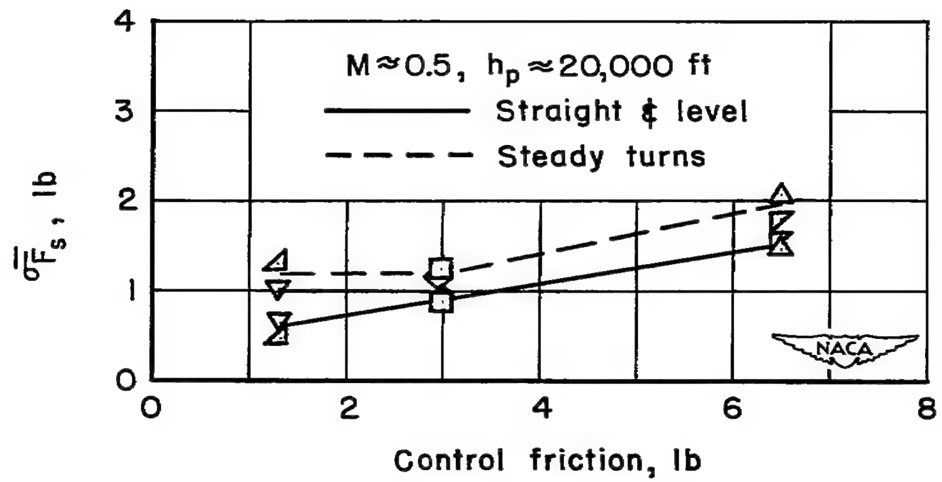

Figure 5.- Average standard deviations of control-force variations.

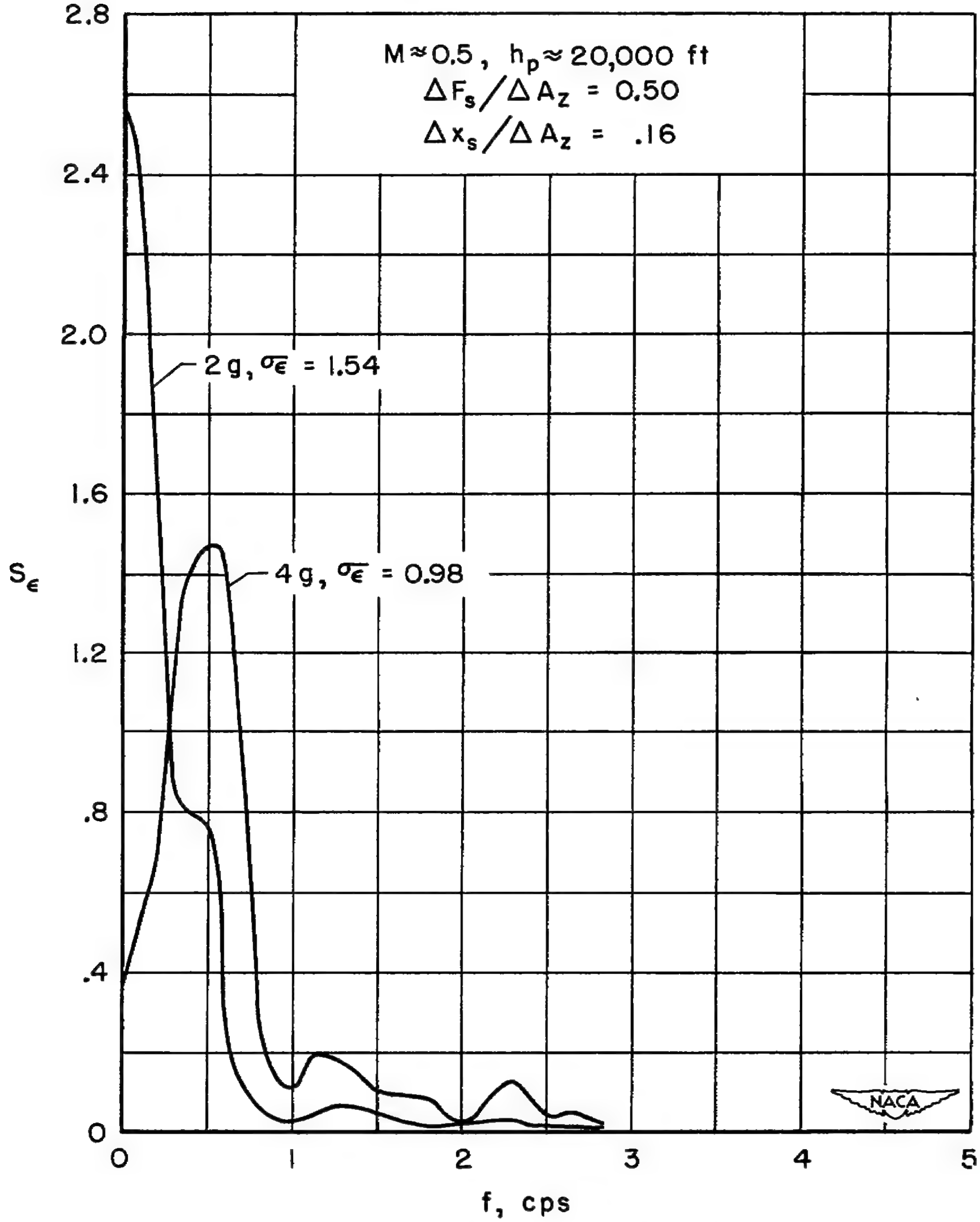

Figure 6.– Normalized spectral densities of aim wander in steady turning tracking.

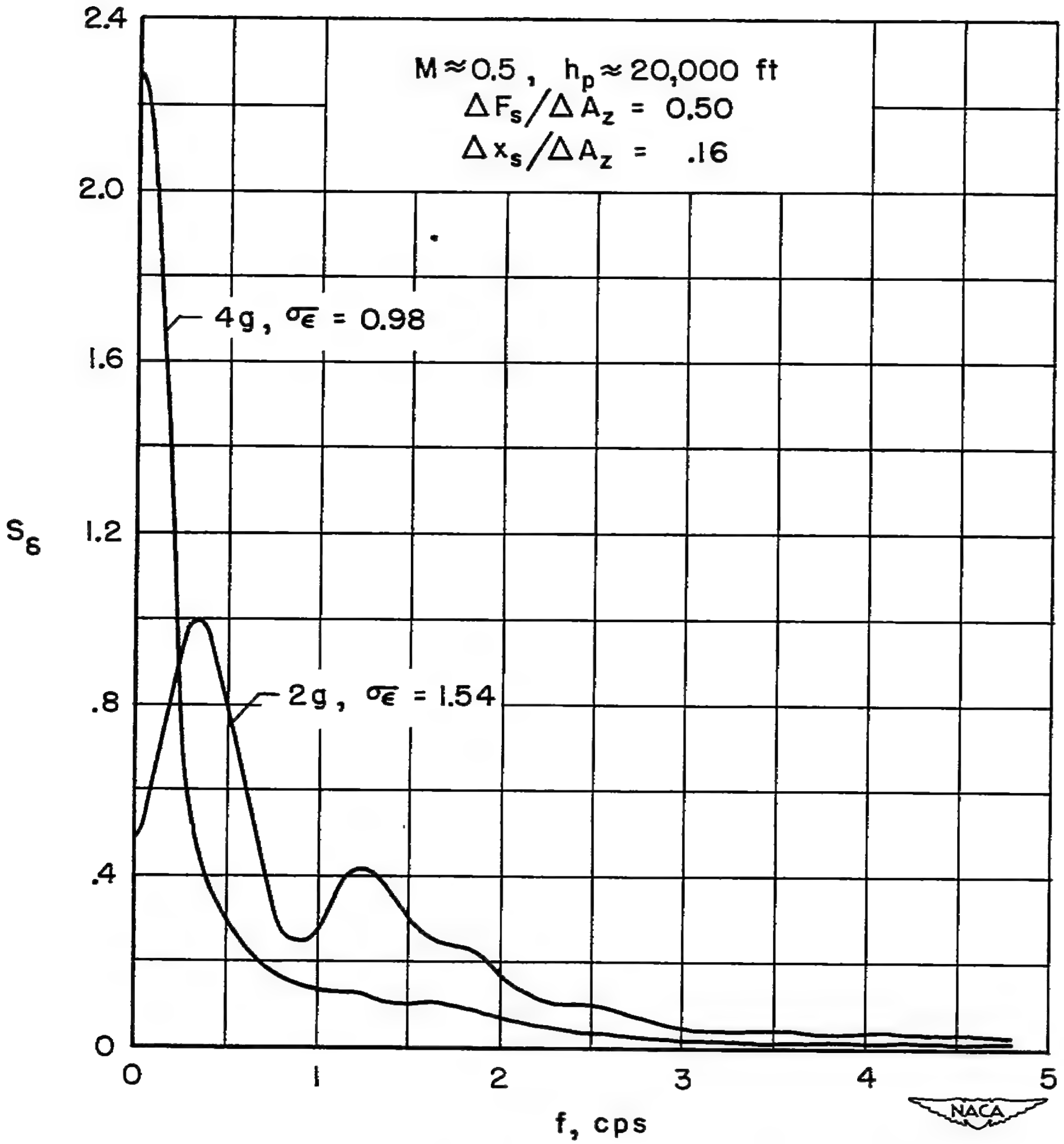

Figure 7.– Normalized spectral densities of elevator movement in steady turning tracking.

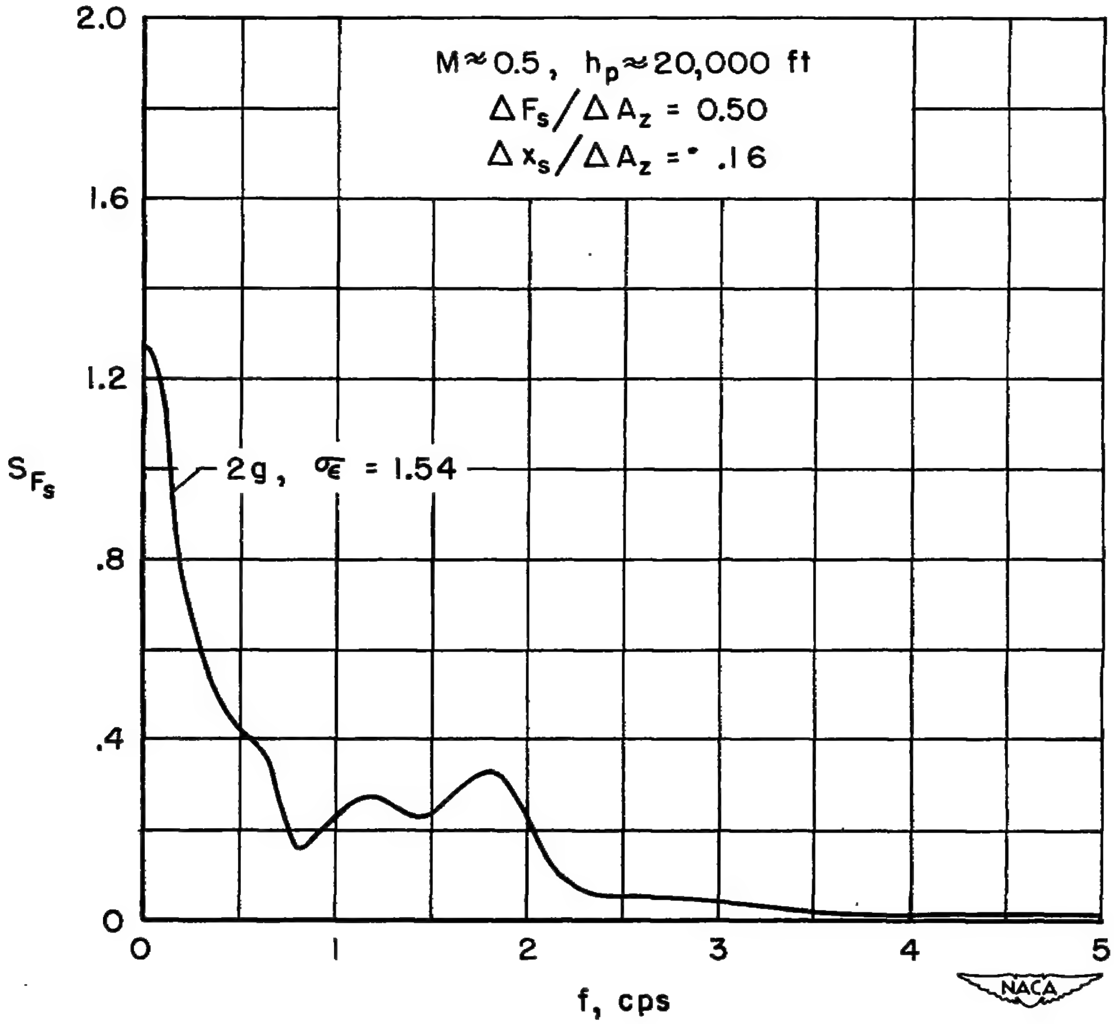

Figure 8.– Normalized spectral density of stick-force variation in steady turning tracking.

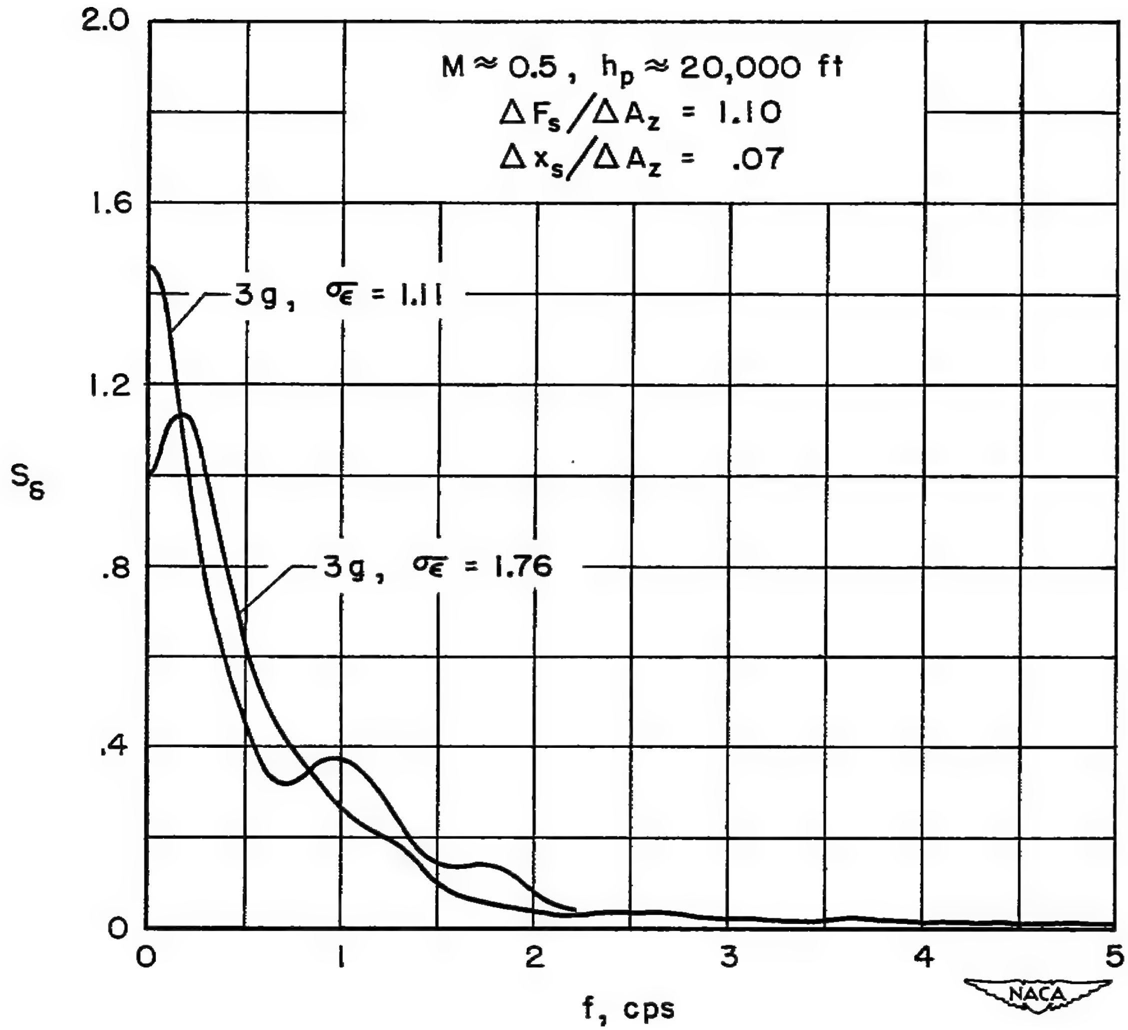

Figure 9.- Normalized spectral densities of elevator movement in steady turning tracking with low control gearing.

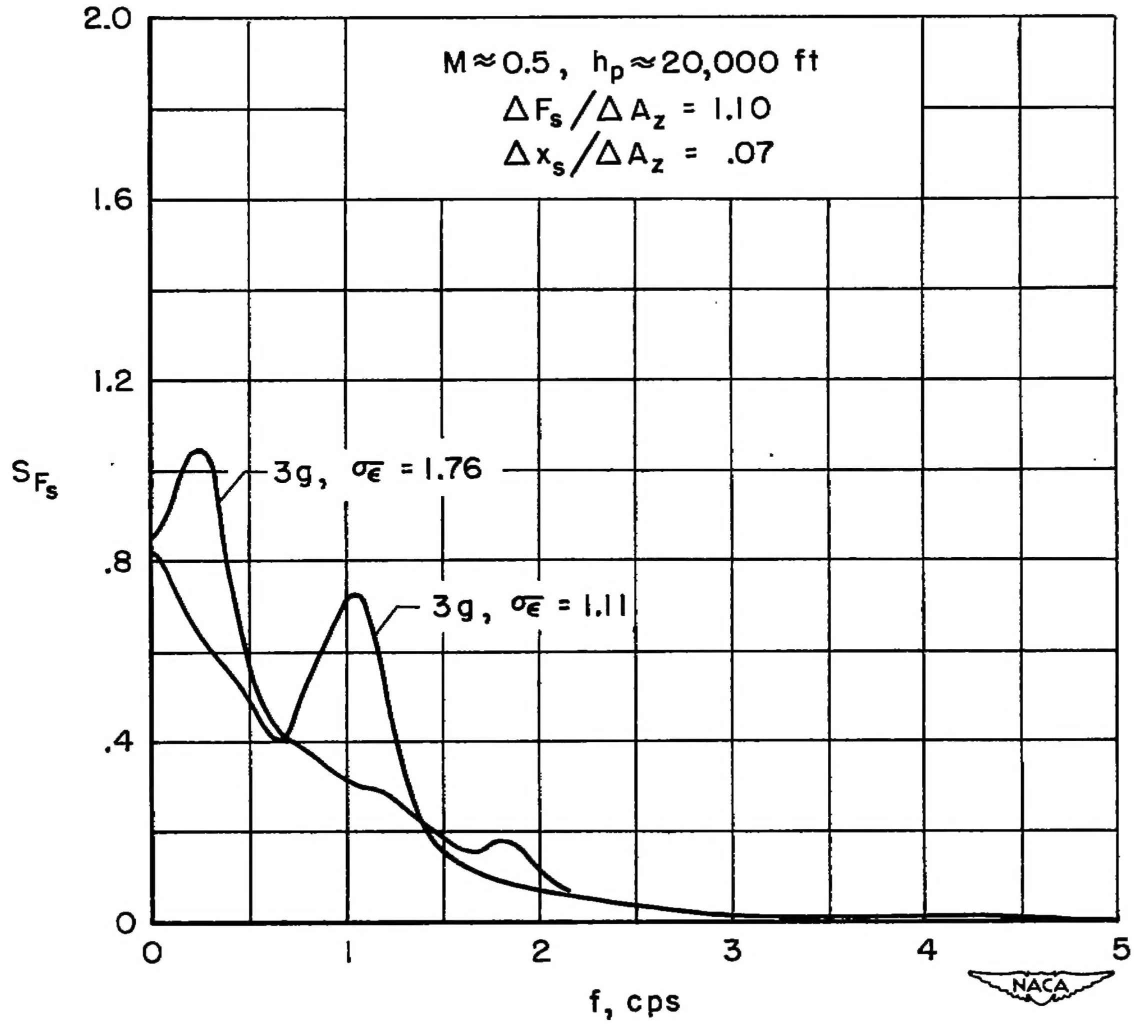

Figure 10.- Normalized spectral densities of stick-force variation in steady turning tracking with low control gearing.

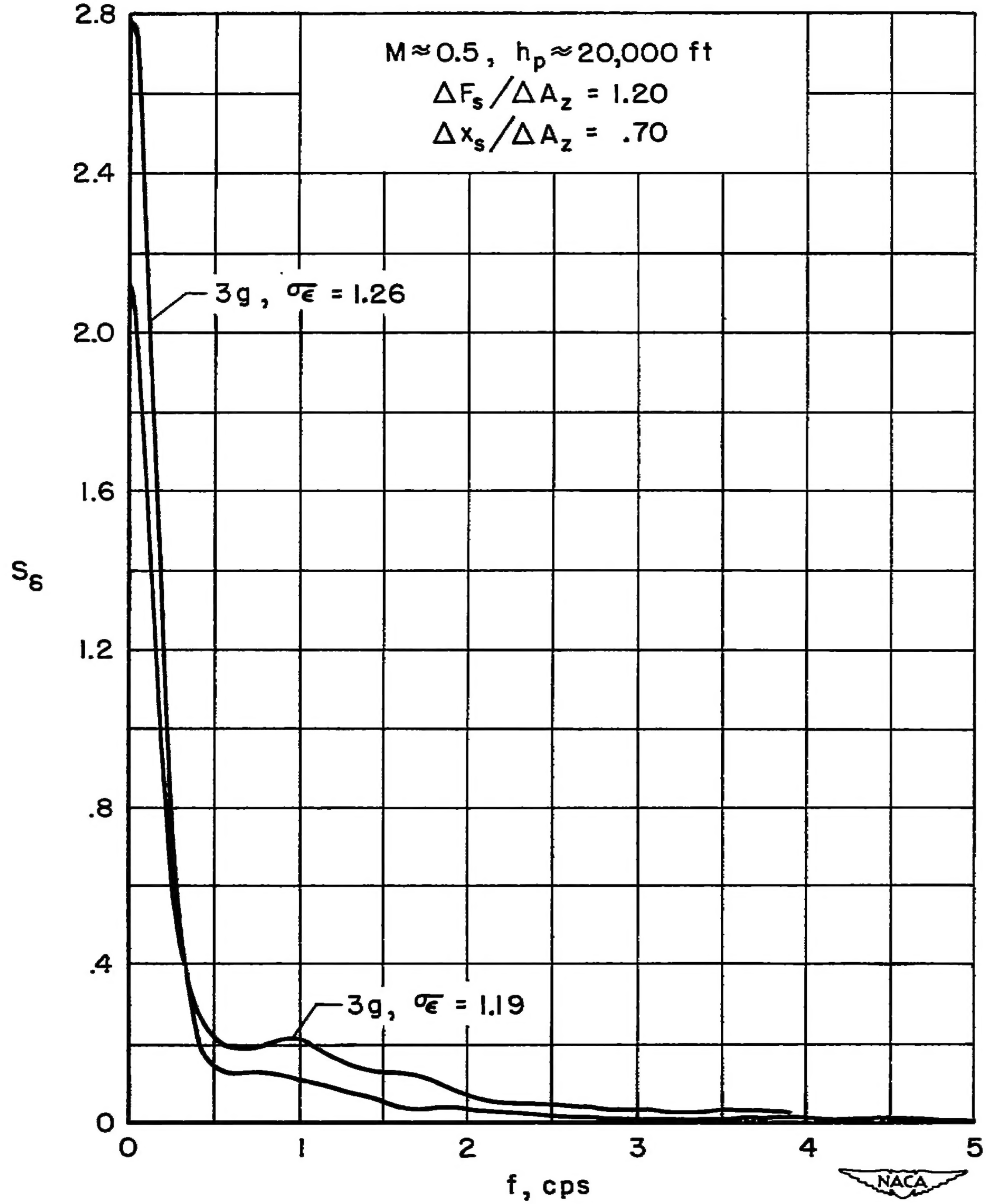

Figure 11.- Normalized spectral densities of elevator movement in steady turning tracking with high control gearing.

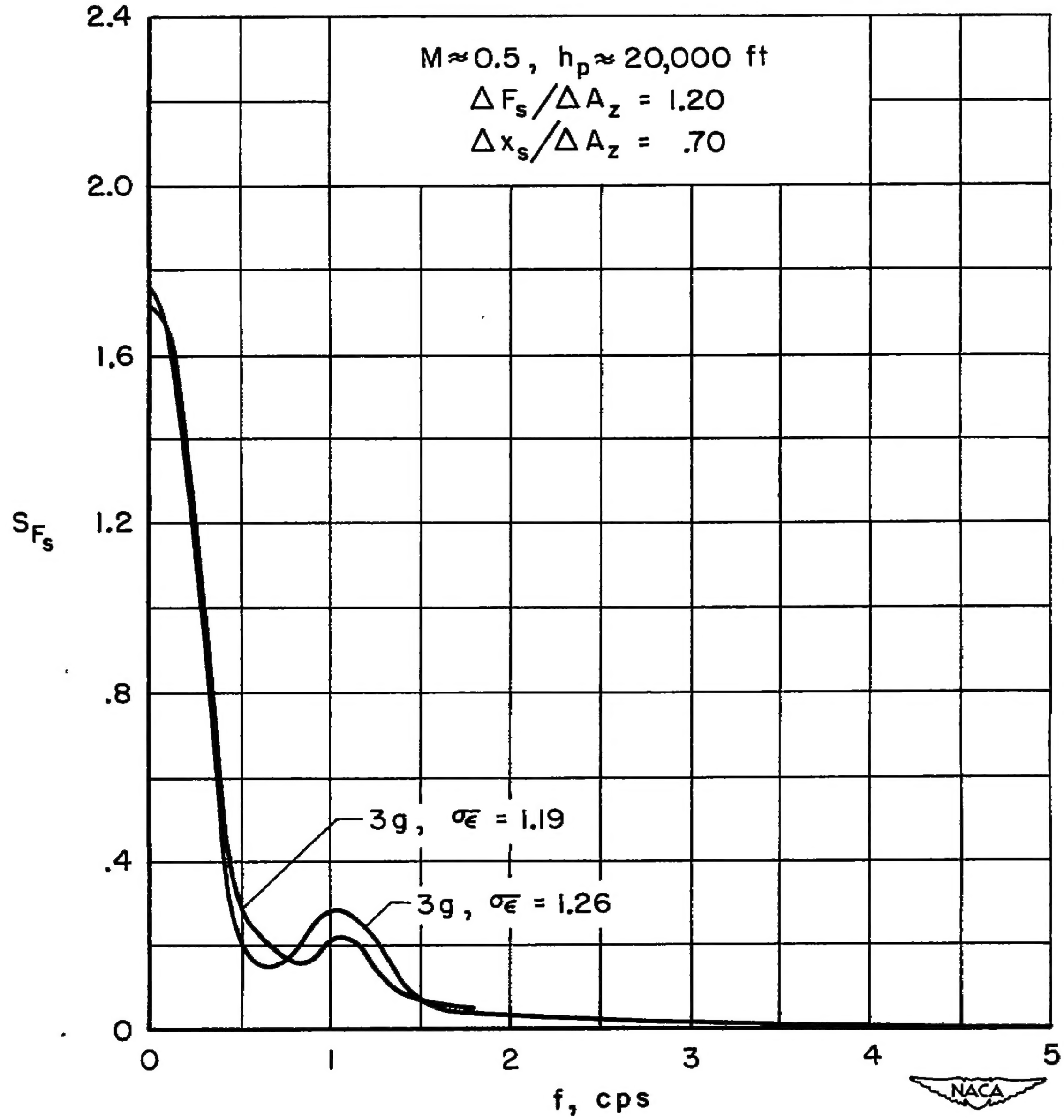

Figure 12.- Normalized spectral densities of stick-force variation in steady turning flight with high control gearing.

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